Development of new polymeric valving unit & coupler for cryogenic fluid control components

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***Abstract* — Cryogenic rocket engine employs a variety of control components to perform various functions like throttling, purging, venting etc. For stringent leak tightness at cryogenic temperature application, polymeric compounds which have good mechanical and physical properties are the main candidate. Requirement for higher seal stress and strength for specific application in high thrust cryogenic engine system components calls for design optimization and exploration of right materials. The search for better polymer materials for cryogenic application is a challenge to control component designers.**

A new polymer, natural Polyether Ether Ketone (PEEK-N), which possesses excellent strength, compatibility & thermal insulation properties at low temperature is a promising one for development of valve seals and thermal isolators. Development of a new material for launch vehicle application involves elaborate characterization and testing. This paper presents the development & qualification of natural PEEK material for a typical valve seal and coupler/thermal isolator used for cryogenic environment. Seals and thermal isolators using PEEK are successfully developed and employed in cryogenic system components.

This paper summarizes the problems encountered in existing materials in cryogenic engine applications, realization of alternate material, design improvements/optimization and results of the various development and qualification tests carried out on PEEK towards these applications.

***Keywords* —** Cryogenic, valve, Polyether Ether Ketone, PCTFE, Phenylon, development, qualification, VESPEL, leakage, thermal isolator, coupler.

I. INTRODUCTION

A number of control components are employed in cryogenic propulsion systems to perform functions like venting, purging, charging and throttling etc. These components have very stringent leak tightness requirement at cryogenic temperatures. The polymeric materials having very good mechanical and physical properties and compatibility with working fluids like Helium, Hydrogen, Nitrogen & Oxygen at cryogenic temperatures are found to be the prominent candidates for sealing and coupling/thermal isolation application. Valve seals and throttle valve couplings are made form polymeric materials like polycarbonate and polyimide. After completion of design analysis of parts, a valve is realized with this material and subjected to different development and qualification tests. The details of the tests and results are given in Section III. Subsequently another valve with natural PEEK seal was realised and supplied for actual application and performance was found satisfactory. Similarly coupler/thermal isolator of natural PEEK was also realized and subjected to different developmental tests which are described in Section IV.

II. NEED FOR NEW SEAL &COUPLER MATERIAL

Different polymeric materials polycarbonate, PCTFE (Poly chloro tri fluoro ethylene), PTFE (Poly tetra fluoro ethylene), Polyimide and Phenylon have been used for sealing and coupling application. Out of these Phenylon has better mechanical and physical properties and is used for high pressure sealing application. But scarcity of this material has hindered production of cryogenic valves. Based on literature survey Polyether Ether Ketone was identified and selected as an alternate option. Subsequently a detail design analysis was carried out. Table-1[9, 10, 11 & 12] gives the typical physical and mechanical properties of different version of PEEK (natural & 30% carbon filled) at room temperature (23^0C). Chemically it is represented as shown in Fig.1.

TABLE 1

Properties	**PEEK**	
	Natural	**30%C**
Specific Gravity	1.32	1.41
Tensile Strength, (MPa)	97(min)	224
Flexural modulus, (MPa)	4099	2019
Shear strength, (MPa)	53(min)	97
Compressive Strength, (MPa)	118(min)	240
Hardness Rockwell	54-59(E)	124®
Elongation (%) Break	>60	>2

Out of these versions natural PEEK is found to be more suitable for our sealing and coupling/thermal isolation application due to its relatively higher percentage elongation and optimum strength compared to other polymers.

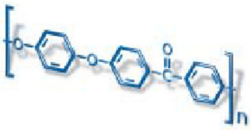

Fig.1 Polymer chain of natural PEEK

Due to a failure of a throttle valve actuator coupling made of polyimide a new alternate was required. A new coupling made from natural PEEK was realised and subjected to a series of development tests.

III. DEVELOPMENT OF SEALING ELEMENT

A. Detail of the valve operation

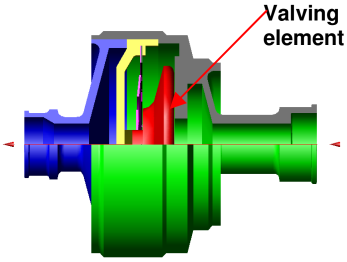

Fig.2 An ideal check valve schematic

Fig. 2 shows the 3-D model (3/4th section) of a typical check valve. The flow of fluid takes place from the right direction as shown in Fig.2. In actual application, initially, valve is in closed condition and valving element will experiences the maximum static pressure from the left side. While in operation, the valving element is lifted due to fluid pressure acting form the inlet side against the spring force and flow takes place. In this condition, valving element experiences only differential pressure across it.

B. Design analysis [1, 2, 3, 4 & 5]

The original design of the valving element made of phenylon was analysed and optimized based upon the material properties for 100bar operating pressure. The present valving element was designed analytically for an operating pressure of 120bar and its design was analysed and optimized based upon the natural PEEK properties with a higher operating pressure of 120bar taking into consideration the operational margin of 20%. Fig.3 gives the 3D model of the disc. Design analysis is completed using ANSYS package for FEM modelling and analysis.

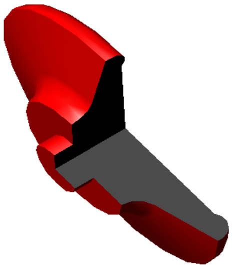

Fig. 3 3-D model of Valving unit (Disc)

Element distribution and stress distribution is shown in Fig. 4 & 5 respectively for an operating pressure of 120bar. The structural analysis shows a localised stressed region of ~95MPa (maximum) which is well below the compressive strength for the polymer and is needed for better leak tightness. The deflection of 0.5mm is also visible in the stress deflection pattern but this is taken care by the support provided at back of the disc.

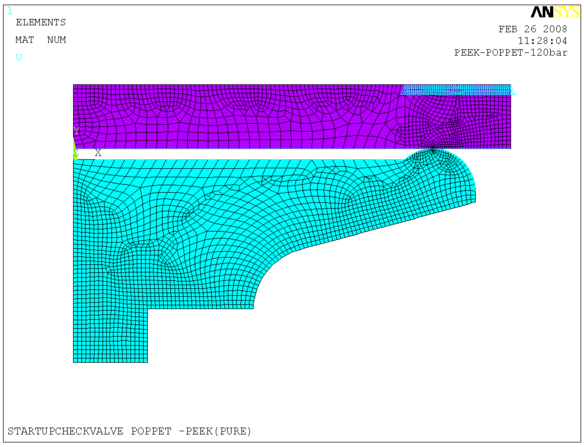

Fig. 4 2-D Axis symmetric model of valving element with distribution of elements

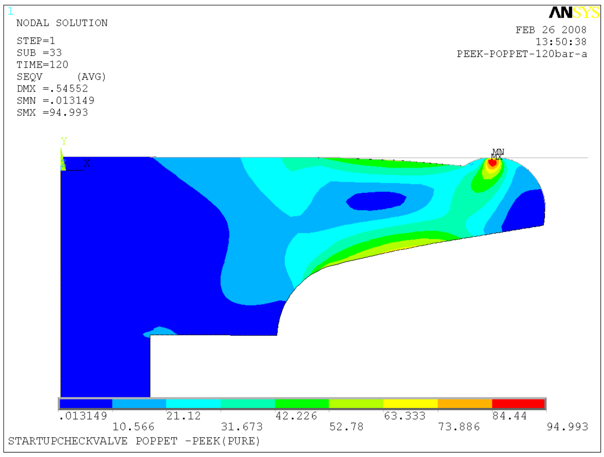

Fig. 5 Stress & displacement distribution in valving

C. Development tests [6 & 7]

Subsequent to satisfactory results achieved from structural analysis two proto models of check valve were made and development test were carried out which included reverse leakage measurement at different outlet pressures after each critical milestone tests. Different stages for development tests are pre-weld, cyclic actuation, post cyclic actuation, post weld, Cryo temperature exposure, post Cryo functional tests. Reverse leak test are considered important for evaluation of performance of natural PEEK valving element. The test results are graphically represented as shown in Fig. 6(a) & 6(b) for two different extreme of operating pressure and on two set of h/w of with phenylon and natural PEEK as valving elements. The development tests were conducted for two different operating pressures of 20bar & 100bar at outlet port of the valve. Matrix of different milestones tests for development test is given in Table-II. All the ambient leak rates are in gaseous nitrogen medium and at Cryo temperature are given in GHe medium. From the test results it is evident that leak rates are very benign compare to specification (**Spec: At ambient ≤ 1.5sccs of GHe and at Cryo temperature ≤ 4sccs of GHe).** This also gives indication that performance of valving element made out of natural PEEK is comparable or better than that of made of phenylon polymer.

TABLE II

Sl. No.	Milestone
1	Pre weld functional test
2	Post cyclic functional test
3	Post weld functional test
4	Cryo temperature functional test
5	Post cryo functional tests

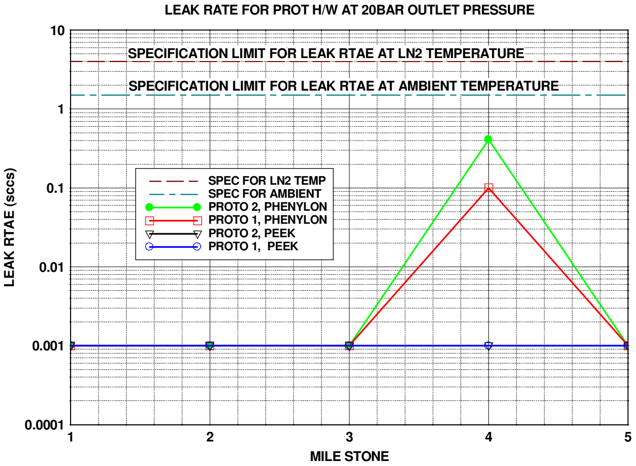

Fig. 6(a) Reverse leak test results at low pressure

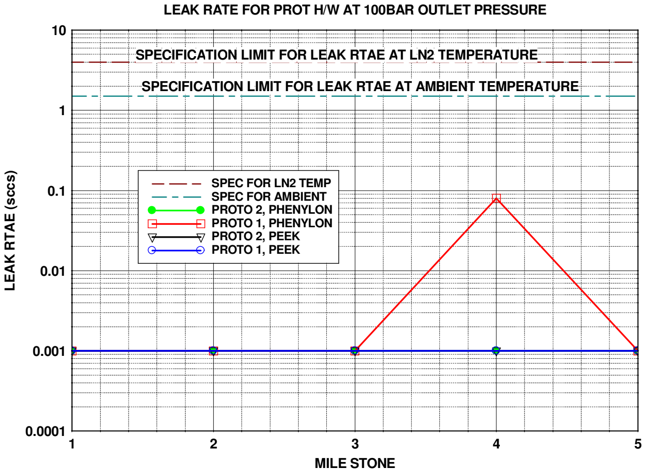

Fig. 6(b) Reverse leak test results at higher pressure

D. Qualification tests [6 & 8]

After successful completion of development test on two proto hardware, qualification test was carried out to demonstrate the margin over the design requirements. These tests comprise vibration (Random, sine, shock), thermal cycling, cyclic actuation test at Cryo temperature to demonstrate cyclic life, humidity test etc. The comparison of leak rates at 20bar and 100bar outlet pressure is shown in Fig. 7(a) & 7(b). All the ambient leak rates are in gaseous nitrogen medium and at Cryo temperature leakage are for GHe medium. Matrix of different milestones for qualification test is given in Table III.

TABLE III

Sl. No.	Milestone
1	Pre weld functional test
2	Post cyclic functional test
3	Post weld functional test
4	Cryo temperature functional test
5	Post Cryo functional tests
6	Random vibration
7	Sine vibration
8	Shock
9-15	Cryo temperature cycling
16	Thermal cycling
17	Humidity

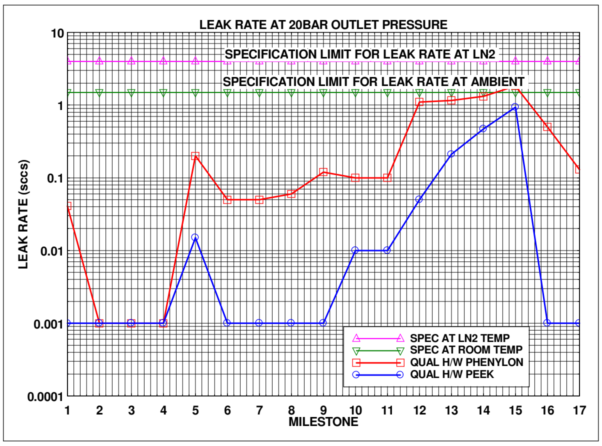

Fig. 7(a) Reverse leak test results at low pressure

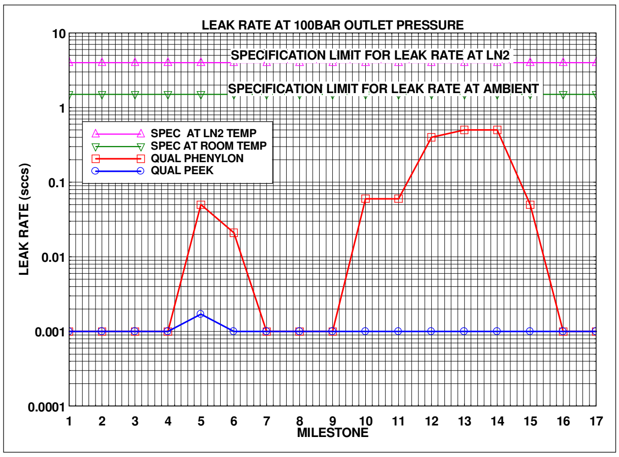

Fig. 7(b) Reverse leak test results at higher pressure

E. Discussion

Successful development and qualification tests indicate that the natural PEEK polymer material selected for the purpose meets all the functional requirements demanded by the service condition of the check valve. Hence natural PEEK polymer can be used as sealing element in similar application.

IV. DEVELOPMENT OF COUPLER / THERMAL ISOLATOR

A. Description of assembly

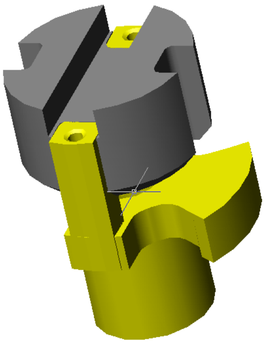

Fig. 8 Throttle valve coupling

A DC motor operated throttle valve used in cryogenic engine is considered in this paper for developmental studies of coupler/thermal isolation mechanism. The rotary motion of the motor is transmitted to the valve carrier with the help of a coupling arrangement which uses a part called cross-piece (Fig. 8).

This cross-piece acts as an Oldham's coupling inside the valve and performs two functions:

a) Acts as a torque transmitter from actuator motor to valve carrier.

b) Acts as a thermal isolator between valve temperature (i.e. 80 K) and actuator drive temperature (i.e. 300 K).

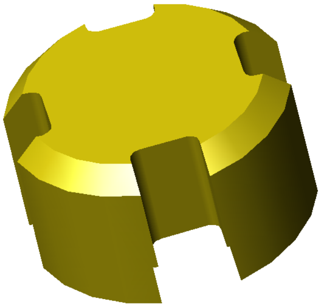

Fig. 9 3-D model of Cross-piece

As shown in the Fig. 9 there are four slots provided in the cross-piece. Into the two diametric opposite slots each, comes the two legs of carrier from valve and actuator drive. Carrier of actuator rotates the cross-piece which in turn rotates the carrier of valve and thus the motion is transmitted form the motor drive to valve.

B. Problem with polyimide cross piece

Initially Cross-pieces made from polyimide were used in the cryogenic engine throttle valve. During development and testing of this valve it was observed that cross-pieces were not able to withstand torques beyond 15 Nm. Cross-piece failures during lab tests were subjected to numerous electron microscopic examinations at 50X magnification from different angles. Some of the views can be seen in the Fig. 10 and 11 revealed failures in shear mode.

Material property comparison for PEEK and Polyimide is given in Table-IV. After considering number of options natural PEEK was proposed to be used. From table IV it can be seen that PEEK (N) is superior to Polyimide in strength and comparable in thermal isolation properties.

TABLE IV

Property	**PEEK(N)**	**POLYIMIDE**
Specific Gravity	1.32	1.2
Tensile Strength, (MPa)	97(min)	80
Thermal conductivity ($X10^{-4}$ cal/cm-sec-^0C)	6	6.9
Flexural strength, (MPa at 23^0C)	170	110
Elongation (%) Break	>60	>7.5
Hardness Rockwell (E)	54-59	45-48

C. Development tests with alternate material

A series of lab tests including torque transmission tests at ambient and Cryo temperature were carried out finished parts followed by radiography. Samples were taken from different batches of Polyimide and natural PEEK cross-piece and were subjected to destructive torque test. Results are given in table V.

TABLE V

S. No.	**Material**	**Observation**
1	VESPEL, V1	Withstood upto 20 Nm
2	VESPEL, V2	Withstood upto 12 Nm
3	VESPEL, V3	Withstood upto 14 Nm
4	VESPEL, V4	Withstood upto 28 Nm
5	VESPEL, V5	Withstood upto 30 Nm
6	PEEK, P1	Withstood > 60 Nm
7	PEEK, P2	Withstood > 60 Nm

Cross-piece is subjected to a service torque up to 15 Nm and considering a factor of safety of 1.5, it should sustain torque values up to 22.5 Nm. But it was found that cross-pieces made from Polyimide were failing at 12Nm, whereas those made from natural PEEK sustained up to 60 Nm. This can be attributed to the production methodology of PEEK polymer rods which is an injection moulded product as compared to Polyimide which are made from compact powder technology and is prone to have internal defects of micron size.

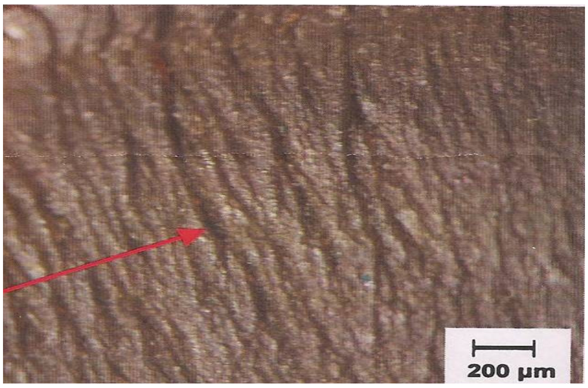

Fig 10 Microscopic View of broken Polyimide cross-piece

These defects are difficult to be detected.

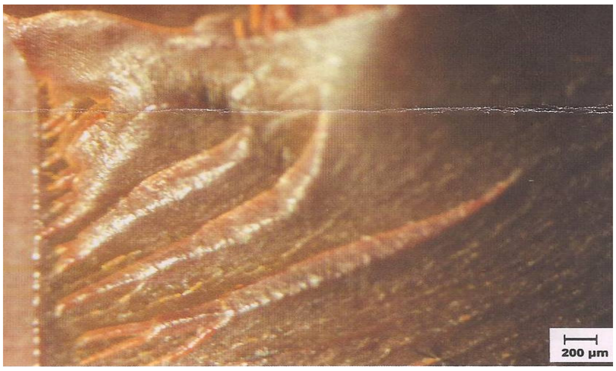

Fig.11 Microscopic View of broken Polyimide cross-piece

D. Discussion

Development test results on the Natural PEEK as a material for cross-piece which is used as a coupler/thermal isolator is very much satisfactory. PEEK cross-piece has behaved exceptionally well in the torque transmission and did not fail even up to torque of 60 Nm. The test could not be carried out beyond this value because of facility limitation. Hence PEEK can be considered as a good replacement for Polyimide as cross-piece material.

V. CONCLUSION

As seen above from results of the development test of PEEK material as a sealing element it can be concluded that it is equally good or better than the existing option of Phenylon polymer.

The tests conducted on throttle valve cross pieces made from natural PEEK are very encouraging and these couplers/thermal isolators work without rupture beyond 60Nm torque compare to 30Nm value for Polyimide material. Hence natural PEEK is a very good option for sealing as well as coupler/thermal isolator elements used in cryogenic application.

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REFERENCES

[1] Aerospace Fluid Components Designer Handbook, Volume 1&2, Technical Documentary No. RPL-TDR-64-25, February 1970, Air force Systems Command, Edwards, California.

[2] ISRO Design Manual, Vol 1. ISRO-PAS-208, Vikram Sarabhai Space Centre, Thiruvananthapuram, November 2005.

[3] C. Amarasekaran, Design Manual for Liquid Propulsion System Fluid Components, Report No. LPSC/CSC/PM/60/11, April 2011; Liquid Propulsion System Centre, Valiamala.

[4] NASA, SPACE VEHICLE DESIGN CRITERIA (CHEMICAL PROPULSION), Liquid Rocket Pressure Regulators, Relief Valves, Check Valves, Burst Disk & Explosive Valves, NASA -8080, March 1973.

[5] Rocket Engine Valve Poppet & Seat Design Data, Technical Documentary, Report No. RPL-TDR-64-68, May 1964, Air force Systems Command, Edwards, California.

[6] NASA, SPACE VEHICLE DESIGN CRITERIA (CHEMICAL PROPULSION), Liquid Rocket Valve Assembly, NASA -8097, November 1973.

[7] NASA, SPACE VEHICLE DESIGN CRITERIA (STRUCTURES), Design Development & Testing, NASA -8043, May 1970.

[8] NASA, SPACE VEHICLE DESIGN CRITERIA (STRUCTURES), Qualification Testing, NASA -8044, May 1970.

[9] VESTAKEEP, POLYETHER ETHER KETONE, Degussa AG, High Performance Polymers' 45764 MARL, Germany.

[10] POLY ETHER ETHER KETONE, Polyscinces, Inc. 400 Valley Road, Warrington, PA 18976.

[11] Ultracomp^{TM} Engineered Thermoplastics, Technical bulletin No. 5264-B1-USA, Parker Han fin, Corporation Salt Lake City, UT 84119.

[12] ASTM Standard Test methods, D638, D695 & D785 for Evaluations of Tensile, Compressive & Hardness properties.